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Deep Level Defects in Alpha Particle Irradiated Silicon Carbide

George C. Rybicki

Photovoltaics Branch

NASA Lewis Research Center

Cleveland, Ohio 44135

ABSTRACT

A Deep Level Transient Spectroscopy (DLTS) study of native and radiation induced defects in MOCVD n on p 6H-SiC diodes has been conducted. Three majority carrier levels were found, at E_v +0.50 eV, E_v +0.55 eV and E_v +0.69 eV, and three minority carrier deep levels were found, at E_c -0.38 eV, E_c -0.48 eV and E_c -0.58 eV. These 6 levels were initally observed in the unirradiated materials. Their concentration increased 2 to 13 fold after irradiation to a fluence of 2 x 10^{11} cm^{-2} 5.5 MeV alpha particles. In addition the carrier removal was monitored during irradiation, and a carrier removal rate of 78050 cm^{-1} for 5.5 meV alpha particles was measured. When compared with a similar study of alpha particle irradiation of InP, the results suggest that SiC has radiation resistance comparable to that of InP, another highly radiation resistant semiconductor.

INTRODUCTION

SiC has a reputation as a highly radiation resistant material. An experimental value of the energy required to displace an atom from its lattice position in SiC, 21.8 eV, is higher than in any other semiconductor but diamond.(1) In addition to its radiation resistance, the wide bandgap of SiC makes it an ideal semiconductor for applications at high temperatures or requiring low leakage currents. This study was undertaken to investigate the use of SiC for radioisotope batteries, an application where leakage current is a major factor affecting the efficiency of power conversion and where radiation resistance affects battery lifetime and power density.(2)

Early studies of radiation resistance and radiation induced defects in SiC were often conducted on Lely grown crystals of 6H SIC. The defects introduced by ion implantation or electron irradiation were investigated by photoluminescence (PL), or electron spin resonance (ESR). The PL results suggested that a divacancy was the predominant defect produced by electron irradiation or ion implantation.(3) A more detailed study by ESR suggested that 5 defects were formed by electron irradiation in n-type 6H-SiC, three charge states of the carbon vacancy, a negatively charged carbon divacancy and a Si vacancy-dopant complex.(4)

Subsequently, the defects in irradiated 3C-SiC grown epitaxially on Si were investigated. Deep levels were observed in a DLTS study of as grown n-type 3C-SiC. Two majority carrier defects were observed, at E_c -0.34 and E_c -0.68 eV.(5) The deeper level was attributed to a surface defect. Neutron irradiation studies of n-type 3C-SiC by DLTS revealed a radiation induced defect at E_c-0.49 eV.(6) Carrier removal studies showed that n-type 3C-SiC had a carrier removal rate for neutron irradiation of 7.2 cm^{-1}, lower than Si under the same irradiation conditions.(6) A similar result was found for 1 MeV electron irradiation where a carrier removal rate of 0.014 cm^{-1} was found for n-type 3C SiC and 0.033 for n-type Si.(7) A deuteron backscattering study of 3C-SiC revealed that an intrinsic defect, the carbon interstitial, was present in epitaxial 3C films. After proton irradiations they concluded that the C atom is displaced preferentially; no Si displacements were found.(8) ESR studies of radiation induced defects in 3C-SiC have also been undertaken: ESR results indicated a defect at the Si site, most probably an isolated Si vacancy, in contrast to the previous work.(9,10) The introduction rate of this defect was 300 cm^{-1} for 2 MeV protons and .02 cm^{-1} for 1 MeV electrons.

Recently single crystal n and p-type 6H SiC wafers have become available. Silicon carbide semiconductor devices are being made by ion

implantation and diffusion or through the growth of epitaxial 6H layers and structures by MOCVD and LPE. Studies of the native and radiation induced defects in these structures have been made.

A DLTS study of 6H SiC diodes formed by ion implantation of aluminum revealed 2 minority carrier deep levels at E_v +0.28 eV and E_v +0.61 eV. The first level was attributed to the ionization energy for the Al acceptor, and the second level was found to be a doublet, at E_v +0.60 and E_v +0.68 eV and was attributed to implantation induced damage.(11) The authors also investigated p-n diodes formed by diffusion of boron. Two minority carrier deep levels were found, E_v +0.35 eV and E_v +0.66 eV. The first level was associated with the ionization energy for the boron donor, and the second level was found to be a doublet, at E_v +0.63 and E_v +0.71, and was associated with a defect/dopant complex. A later study by the same authors identified a majority carrier defect at E_c -1.06 eV in Al ion implanted p-n diodes.(12)

Boron related deep levels have been studied in p-type LPE boron doped epilayers and in ion implanted boron doped 6H-SiC. The ionization energy of the boron dopant was determined to be 0.32 eV.(13) Two majority carrier deep levels were found by DLTS, Ev + 0.30 eV and Ev +0.58 eV. The

first was attributed to the isolated boron acceptor and the second to a complex of the boron dopant atom and a native defect.

Radiation damage in 6H SiC JFETS has been studied using neutron irradiation: a carrier removal rate of 4.5 cm^{-1} was estimated from changes in the transconductance and pinch off voltage.(14) A DLTS study of electron irradiated n-type SiC revealed three majority carrier radiation induced deep levels at E_c -0.35 eV, E_c -0.60 and E_c -1.10 eV.(15) These defects were stable and did not anneal out at temperatures up to 1300 K.

Native defects in n-type 6H-SiC Lely crystals have been studied by DLTS. Two majority carrier deep levels have been found at E_c -0.62 eV and E_c -0.64 eV.(16) These two centers could also be generated by irradiation or ion implantation. The defects were thought to be due to the V_C-V_{Si} divacancy by correlation with a similar study by EPR. (17) Two additional majority levels were detected at E_c -0.35 eV and E_c -0.57 eV in electron irradiated n-type SiC, but no comment was made on their nature.(16)

In summary, several defects are commonly found by DLTS in n-type SiC. The minority carrier level at E_v +0.66 is associated with a boron defect complex, and the level at E_v +0.61 is associated with radiation damage.

Majority carrier levels at E_c - 0.62 , E_c -0.64 and E_c -1.1 eV are associated with defects formed during growth or by ion implantation and electron irradiation; the first two levels are associated with the divacancy. In boron doped p-type SiC two majority carrier deep levels are found, E_v +0.30 and E_v +0.58 eV. The first level is associated with the isolated boron dopant and the second with a boron-defect complex.

It can be seen that relatively less work has been done on p-type SiC materials. New technology may require more information on p-type SiC and for the applications in this study that was true. A DLTS study of radiation damage in n on p-type SiC diodes has thus been undertaken.

EXPERIMENTAL

SiC n on p ultraviolet (UV) photodiodes were purchased from Cree Research Inc., Durham NC. Details of the structure and characteristics of the diodes are described elsewhere, but briefly, they are composed of a p-type SiC substrate with an aluminum doped p-type epitaxial layer and nitrogen doped n-type emitter.(18) The diodes were analyzed by CV and DLTS before irradiation. A carrier concentration in the base of 2.25×10^{16} cm^{-3} +/- 0.6 was determined. The samples were then irradiated, under vacuum, to a fluence of 2 $x10^{11}/cm^3$ with 5.5 MeV alpha

particles from an Am-241 radioisotope source. After the irradiation the carrier concentration was measured again and the samples were analyzed using DLTS. DLTS analyses were conducted under 4 volts reverse bias and with fill pulses of 4 volts for majority carrier conditions and 8 volts for minority carrier conditions.

RESULTS

The majority and minority DLTS spectra of the unirradiated SiC diodes are presented in Figures 1 and 2. Three minority and three majority deep levels were present in the unirradiated samples. The DLTS spectra of the irradiated samples are presented in Figures 3 and 4. The DLTS spectra of the irradiated samples were degraded somewhat over the unirradiated spectra and only two peaks could be resolved in both the majority and minority carrier DLTS spectra. The concentration of the defects was calculated from the peak heights, and the activation energies of the deep levels were determined. The capture cross sections were calculated from the intercept of the curves used in determining the activation energies. The data extracted from the DLTS spectra are found in Table I. In addition, in a separate experiment, the doping concentration was measured as a function of alpha particle fluence during irradiation and the carrier removal rate was calculated. The carrier removal data are presented

graphically in Figure 5.

The carrier removal rate of 78050 ± 16575 carriers per 5.5 MeV alpha particle measured here is quite high. A carrier removal rate of 4.5 cm^{-1} per 1 MeV equivalent neutron fluence has been observed during neutron irradiation of 6H SiC (14). In 3C SiC a carrier removal rate of .014 cm^{-1} was measured for 1 MeV electrons.(10) In a study of neutron irradiated 3C SiC a carrier removal rate of 7.2 per 1 MeV equivalent neutron was measured.(6) The three previous authors all state that their measured carrier loss was less than that observed in silicon under similar irradiation conditions. Relatively less data is available for alpha particle irradiations of common semiconductors. A carrier removal rate of 73400 ± 15800 per 2 MeV alpha particle was measured in p-type InP.(19)

The carrier removal rate in SiC is expected to be lower than in Si or many other semiconductors due to the higher displacement threshold in SiC.(1) For a carrier to be trapped at a radiation induced defect the defect must first be created and the higher the displacement energy the lower will be the defect introduction rate. The high rate of carrier removal caused by alpha particles versus other particles is a result of several factors. Lattice atoms are displaced and defects created by Rutherford

scattering between the lattice atoms and the incident particle. The cross section for Rutherford scattering can be described by the relation

$$\sigma_d = \frac{\pi}{4}\left(\frac{2Z_1Z_2e^2}{\mu v^2}\right)^2 \frac{E_p}{E_d} \quad , \qquad (1)$$

where σ_d is the displacement cross section in cm^2, Z_1 and Z_2 are the charges of the particle and target atoms, e is the electronic charge, u is the reduced mass, mM/(m+M), where m and M are the masses of the particle and target atoms respectively, v is the particle velocity, E_p is the incident particle energy and E_d is the energy required to displace a lattice atom.(20) Since the charge on the alpha particle is higher and its velocity lower than a neutron or electron, it has a higher displacement cross section and will undergo more collisions per unit path length. In addition, the maximum energy transferred to the displaced atom in a collision, given by the relation

$$E_{max} = \frac{4mME_p}{(m+M)^2} \quad , \qquad (2)$$

is higher for an alpha particle than for an electron or neutron, and thus a particle displaced by an interaction with the alpha particle itself gains a larger amount of energy and can cause more secondary displacements.(20) The higher displacement rate results in more defect production and thus

more carrier removal.

The DLTS spectra revealed the presence of three majority carrier levels, E_v +0.50 eV, E_v +0.55 eV and E_v +0.69 eV in the unirradiated SiC and two levels, E_v +0.55 eV and E_v +0.69 eV in the irradiated SiC. The two levels at E_v +0.50 eV, E_v +0.55 eV are close in energy and capture cross section to the level E_v +0.58 eV with capture cross section of $10 \pm 5 \times 10^{-15}$ cm^2, reported in boron doped SiC (13). This defect is referred to as the D center and is commonly found in B doped materials. In this case boron was not intentionally added to the samples but its presence as an unintended impurity has not been ruled out. The deeper level is close in energy to the level E_v +0.66 eV reported for an aluminum-defect complex in ion implanted SiC(11).

The minority carrier DLTS spectra revealed the presence of 3 levels at E_c -0.38 eV, E_c -0.48 eV and E_c -0.58 eV. A level at E_c -0.35 eV, and named the E center was reported in electron irradiated n-type SiC but no cross section measurement was performed.(16) No suggestion was made as to the nature of this defect other than that it was found in irradiated SiC materials. Another possibility is that the levels observed at E_c -0.38

eV and E_c -0.48 eV are Al dopant-defect complexes as suggested by the observation of levels with activation energies of 0.39 and 0.49 eV in the photoluminescence spectra of Al ion implanted SiC.(21) The level observed at E_c -0.58 eV is in reasonable agreement with the Z center observed at E_c -0.62-0.64 eV in as grown and electron irradiated SiC.

No new defects were formed after irradiation although the concentration of defects increased considerably. The DLTS spectra were degraded somewhat after irradiation and it became more difficult to resolve all three peaks in the post irradiation spectra. As a result only two minority and two majority carrier peaks were found in the irradiated SiC. The concentration of the majority carrier levels increased 2 to 6 times while the concentration of the minority carrier levels increased 10 to 13 times. The minority carrier peaks increased more strongly than the majority carrier peaks despite the fact that substantial carrier removal was observed. This suggests that majority carriers may be trapped at levels deeper in the band gap and not revealed by DLTS. Levels deeper in the band gap than those found here are difficult to observe by DLTS as the thermal emission of carriers at commonly used analysis temperatures is too slow to be observed by most DLTS equipment. The range of deep levels visible can be extended by running the DLTS spectra to higher

temperatures than the 400 K used here, but that was not possible using our equipment.

DISCUSSION

The fact that no new defects were created after irradiation suggests that all the levels observed were due to native defects or native defect-dopant or impurity complexes. The observation of defects as either native or radiation induced in SiC is not new. The Z center in n type SiC has this type of behavior in both epitaxially grown or Lely SiC samples. The minority carrier levels found here are in reasonable agreement with those previously observed in SiC and named the E and Z centers. The majority carrier deep levels are in reasonable agreement with the values for the D center in SiC and although the samples here were not intentionally B doped, trace boron contamination cannot be ruled out. The D center has been observed in DLTS studies of MOCVD diodes that were aluminum doped. The D center was thought to be formed as a result of unintentional contamination of the sample with boron.(22) The deepest level observed here at E_V +0.69 eV is close in energy to an alternative measurement of E_V +0.66 eV as the level for the D center.(11) The conclusion is then that the minority carrier levels observed in these samples are the E and Z centers and that the majority carrier levels are due to trace boron contamination leading to the formation of the D center.

The results on carrier removal, defect concentration and defect introduction rates found in this study are somewhat difficult to compare due to the scarcity of alpha particle irradiation studies in semiconductors. The work on alpha particle irradiation of InP mentioned earlier, although done on similarly doped material, was done on Schottky barrier diodes and with 2 Mev versus 5.5 Mev alpha particles. The results of the two studies must thus be compared carefully. The results can be scaled for alpha particle energy using the computer code TRIM (The Range of Ions in Matter) to compare the non-ionizing energy loss of the particles in a target material. (23) This approach has been sucessfully used to compare damage produced by several types and energies of particles in GaAs. (24) Using this code to compare the nuclear stopping power of 5.5 MeV vs. 2 MeV alpha particles, it was predicted that the 2 MeV alpha particles were more damaging than 5.5 MeV alpha particles by 2.35 times. (23) The higher energy of the 5.5 MeV alpha particles reduced the collision cross section and resulted in a longer mean free path between collisions. A lower defect introduction rate is expected for the higher energy particles.

The carrier removal rate for 5.5 MeV alpha particles in SiC was 78050 ± 16575 per particle versus 73400 ± 15800 per 2 MeV alpha particle in

InP. (19) The carrier removal rate, when corrected for the energy differences, is predicted to be several times larger in SiC than in InP. The majority carrier defect introduction rates measured, however, are much lower in SiC than in InP. Defect introduction rates measured for SiC were 139 and 165 per 5.5 MeV alpha particle versus 5870 and 9000 per 2 MeV alpha particle in InP. The defect introduction rate for majority carrier defects even after correction for the higher damage constants in InP is considerably lower in SiC. No data was available for minority carrier defect introduction rates in alpha particle irradiated InP.

Data is however available for 0.2 MeV proton irradiation of InP p-n diodes. The nuclear stopping power of 0.2 MeV protons in InP is approximately equal to the nuclear stopping power of 5.5 MeV alpha particles in InP. This offers the opportunity to compare the results of 5.5 MeV alpha particle irradiation of SiC and InP. In the case of 0.2 MeV proton irradiation the defect introduction rates in InP were 685 minority carrier and 1355 majority carrier defects per particle. (25) In SiC the defect introduction rates were 1804 minority carrier defects and 304 majority carrier defects per particle. The total defect introduction rates are almost equal in InP and SiC and thus the radiation resistance of InP and SiC are predicted to be very similar. These comparisons however must be

viewed carefully due to the approximate nature of the correction in damage production.

CONCLUSIONS

A DLTS study of unirradiated and alpha particle irradiated SiC revealed three minority and three majority defect levels. These levels were present in both virgin and alpha particle irradiated materials. This suggests that intrinsic defects or defect complexes are formed during MOCVD growth of SiC, as the production of lattice displacements by irradiation did not produce any new levels. The concentration of these defects increased 2 to 13 fold after irradiation with 5.5 MeV alpha particles. The total defect introduction rate for the alpha particle irradiation is about comparable to what might be expected under similar conditions in InP, another highly radiation resistant semiconductor. Carrier removal in SiC was compared with a similar study of alpha particle irradiated InP and the rate of carrier removal is predicted to be somewhat higher in SiC.

Table I: Summary of DLTS Data for Unirradiated and Irradiated SiC diodes.

Peak ΔE	Cross Section σ_∞	Pre-Irradiation Concentration x 10^{13} cm^{-3}	Post-Irradiation Concentration x 10^{13} cm^{-3}
E_V + 0.69	1.34 x 10^{-16} cm^2	2.26 ± 0.89	5.04 ± 1.3
E_V + 0.56	1.97 x 10^{-15} cm^2	0.56 ± 0.08	3.86 ± 0.60
E_V + 0.50	1.86 x 10^{-14} cm^2	1.01 ± 0.17	----------
E_C - 0.58	4.08 x 10^{-17} cm^2	2.15 ± 0.56	18.3 ± 0.10
E_C - 0.48	8.89 x 10^{-17} cm^2	2.00 ± 0.33	----------
E_C - 0.38	2.92 x 10^{-17} cm^2	1.35 ± 0.28	21.3 ± 0.25

List of Figures

Figure 1. Majority carrier DLTS spectrum of unirradiated SiC.

Figure 2. Minority carrier DLTS spectrum of unirradiated SiC.

Figure 3. Post irradiation majority carrier DLTS spectrum of Am-241 irradiated SiC.

Figure 4. Post irradiation minority carrier DLTS spectrum of Am-241 irradiated SiC.

Figure 5. Carrier removal in Am-241 irradiated SiC.

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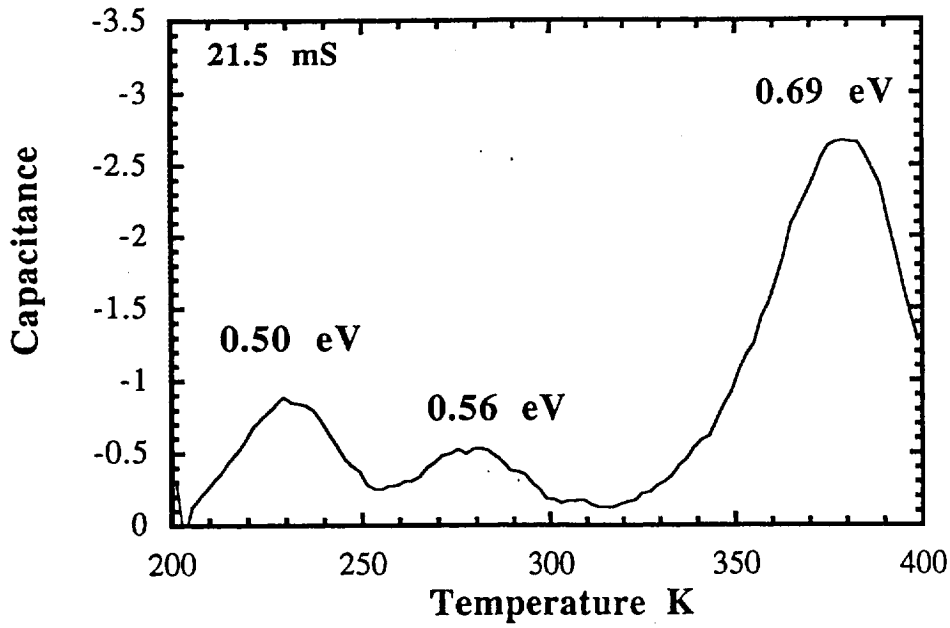
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350
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Temperature K

Figure 1.

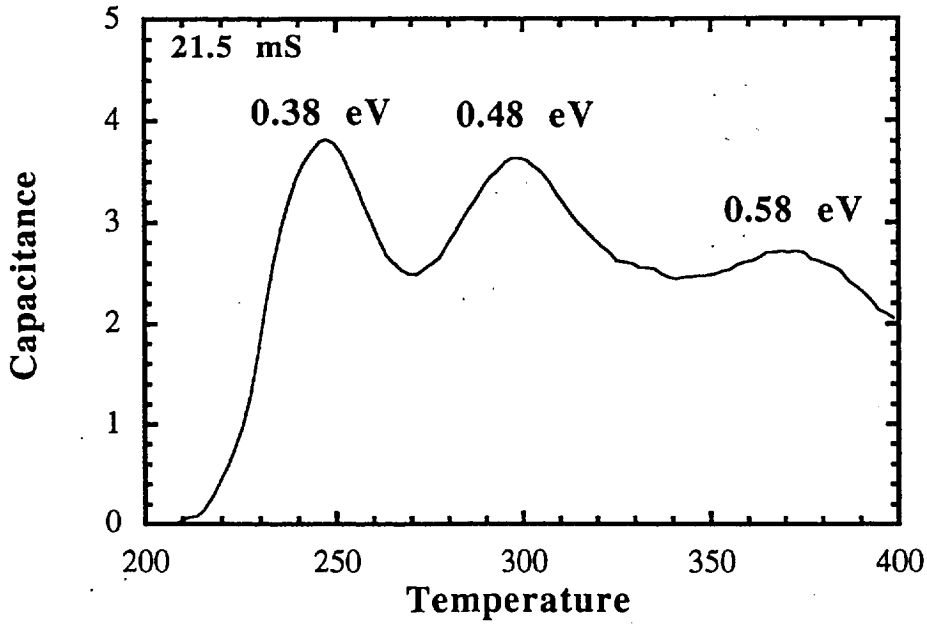
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Figure 2.

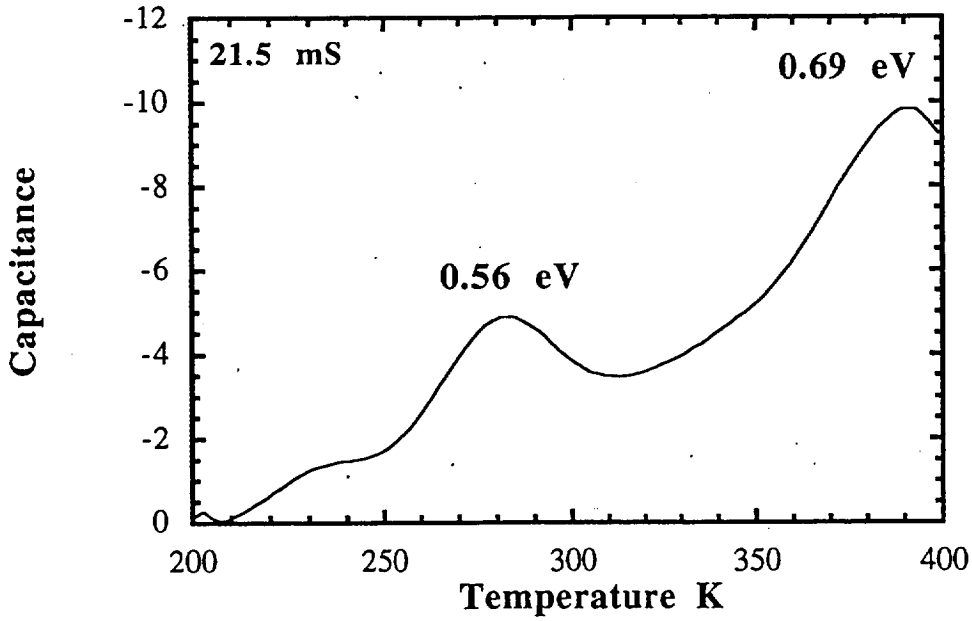
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Figure 3.

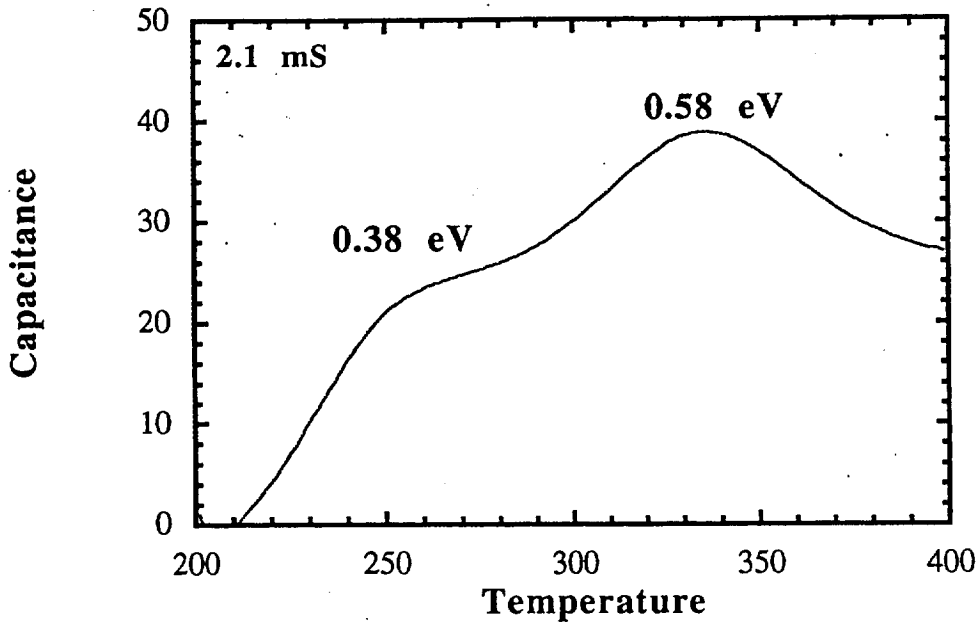
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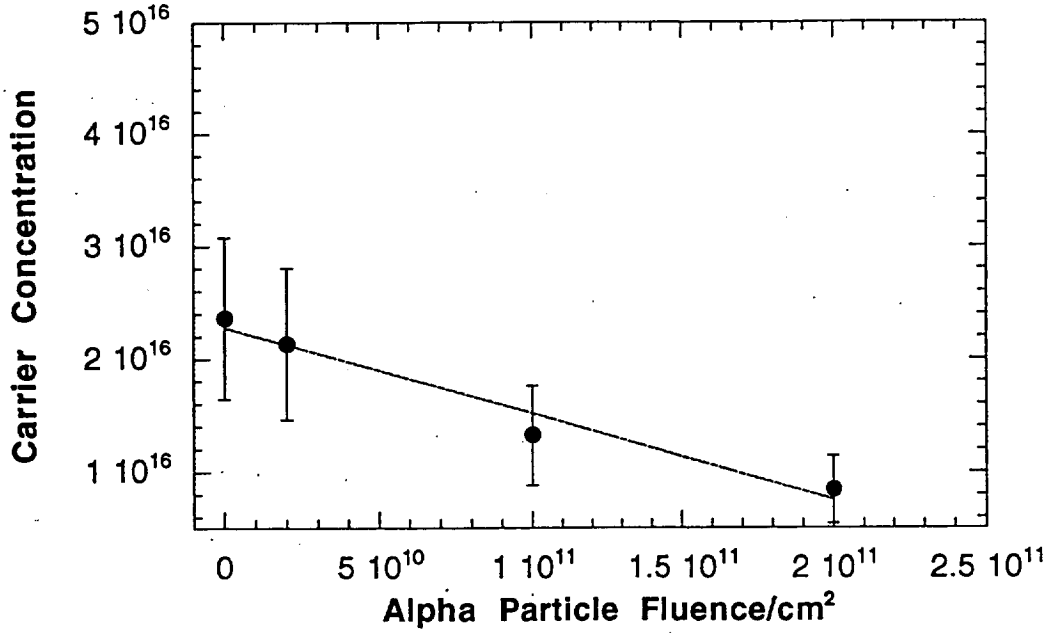
Figure 4.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2 10^11
2.5 10^11
Alpha Particle Fluence/cm^2

Figure 5.